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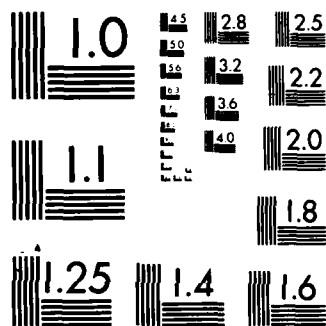
DETERMINATION OF THE COMBUSTION MECHANISMS OF
ALUMINIZED PROPELLANTS(U) PURDUE UNIV LAFAYETTE IN
SCHOOL OF AERONAUTICS AND ASTRONAUTI.

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particle size analyzer and a pulse-lit photographic technique. In this paper, the servo-controlled strand window bomb is briefly described. The theory and operation of the imaging-type, particle size analyzer to be employed is detailed. Finally, the feasibility of using pulse-lit photography within a study of metal particle/agglomerate combustion is discussed along with the presentation of such photographs taken.



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Final Report ¹⁷
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**DETERMINATION OF THE COMBUSTION MECHANISMS
OF ALUMINIZED PROPELLANTS**

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I. INTRODUCTION MATTHEW J. KANE
Chief, Technical Information Division

The use of metalized solid propellants may lead to decreased motor efficiencies due to two phase flow effects as well as incomplete metal particle/agglomerate combustion. To be confident of two phase flow loss predictions, information must be obtained regarding the metal particle/agglomerate size and size distribution throughout the motor chamber and nozzle. Furthermore, factors controlling the combustion efficiency of metalized propellants are the size of the metal particles/agglomerates, their burning rate characteristics, and their residence time in the rocket motor combustion chamber. Analytical combustion efficiency analyses [1,2] must be based on trajectory calculations for individual metal particles/agglomerates in the combustion chamber flow-field, accounting for gas/particle velocity and thermal lags (two phase flow effects) and metal particle/agglomerate burning behavior.

In order to predict mechanisms for describing metal particle/agglomerate chemical and physical size change in the flowfield of a nozzle, one must be able to accurately specify the initial metal particle/agglomerate size and size distribution at the entrance of the nozzle. Therefore, it is important that the various mechanisms influencing the combustion of metal as well as the physical and chemical characteristics of the burning metal particle/agglomerate as it leaves the propellant surface and traverses the motor chamber be well understood.

Two important aspects of metal particle/agglomerate behavior were investigated. These being: (1) the surface/near surface particle agglomeration mechanism and (2) the metal particle/agglomerate combustion mechanism within

the motor chamber flowfield. The surface/near surface behavior is important since the metal particle/agglomerate size and combustion characteristics must be examined in order to observe their relationships with both motor operating conditions and propellant formulation variables. Also, motor chamber flowfield behavior along with metal particle/agglomerate combustion behavior is required for combustion efficiency calculations.

The approach for analyzing the mechanisms involved in metalized propellant combustion made use of a laboratory scale, motor flowfield simulating device in conjunction with both an imaging-type particle size analyzer [3,4] and a pulse-lit photographic technique [5]. The flowfield device consists of a servo-positioning, high pressure window bomb [5,6] coupled to a PDP-11 mini-computer for data acquisition/reduction. Both the imaging-type particle size analyzer and the pulse-lit photographic technique are unique in their application to solid propellant research in that they should prove to be accurate, non-intrusive diagnostic tools for making metal particle/agglomerate size and size distribution measurements within simulated motor chamber flowfields.

II. SERVO-POSITIONING STRAND WINDOW BOMB

In an effort to determine mechanisms influencing aluminum particle surface/near surface agglomeration/ignition/combustion behavior, detailed experimental observations of these processes must be conducted. Especially important is that one must be able to observe the processes occurring on or near the surface during the combustion of aluminized propellants in controlled environments. One such laboratory tool that has been proposed for long duration observation of the burning process is a servo-controlled propellant strand burner. The purpose of such a device is to continuously feed a

strand of propellant into a controlled pressure/flow environment at a rate equal to its burning rate. With this constraint satisfied, the propellant surface is held fixed in space for the entire duration of the strand burn, thus permitting ample time for observation. In an earlier reference by the authors [5], the limited research efforts directed toward developing such an apparatus over the past three decades have been reviewed. In that paper, the servo-positioning strand window bomb currently in operation at Purdue University is described [6].

The servo-controlled strand window bomb is a modified Crawford bomb designed for a maximum pressure of approximately 7 MPa. A 2 milliwatt He-Ne laser is used as a source of light which is aimed across the propellant surface and focused upon a photo-detector. The photo-detector output is thus proportional to the position of the propellant within the beam. By introducing this electrical signal into the feedback circuitry powering a to its burning rate. In Ref. 6., the servo-positioning strand window bomb has been shown to operate successfully during the combustion of several AP-based, non-aluminized propellants at pressure levels up to a maximum of 2.5 MPa. During a typical test sequence, a PDP-11 mini-computer data acquisition system acquires all pertinent servo-positioning system data along with additional experimental data such as combustion pressure. With the acquisition of servo-motor propellant feed rate versus time data, an instantaneous propellant surface position can be determined as a function of time. In Ref. 5, a typical surface position versus time trace has been presented. After an initial start-up transient, the burning propellant surface was observed to be held within +/- 100 microns - or on the order of the surface roughness for the AP-based propellant formulation considered. Since Ref. 5 was written, modifica-

tions have been made thus improving the response of the propellant feed system so that the burning surface can be held even more stationary - a necessary requirement for the experimental investigations of the surface/near surface behavior of aluminized propellants described below.

III. PROPELLANT SELECTION

In this investigation of combustion mechanisms associated with the burning of aluminized composite solid propellants, six specific propellant formulations have been selected for study. Table I presents these six formulations. Each propellant is comprised of a unimodal ammonium perchlorate (AP) oxidizer fraction, a prescribed percentage of aluminum powder and a HTPB binder. The oxidizer has an "as received" coarse particle grind characterized by a fifty percent weight mean diameter of 190 microns and a calculated mode width parameter [7] of 1.6. The aluminum powder used is nearly monodisperse, or all one diameter, reported by the manufacturer as being approximately 18 ± 4 microns. The first formulation, Prop. 1, subsequently referred to as the baseline propellant, consists of 65 percent (by mass) AP and 15 percent aluminum powder. The O/F ratio (the ratio of the AP fraction to the binder fraction, on a mass basis) is 3.25. The next two formulations, Prop. 2 and Prop. 3, have been selected to vary the O/F ratio about the baseline value of 3.25. The mass fractions of the ingredients correspond to either a doubling (Prop. 2) or halving (Prop. 3) of the expected aluminum agglomerate particle size based on a simple "pocket model" calculation [8]. The variation in the O/F ratio between these two propellants and the baseline formulation also corresponds to either a decrease (Prop. 2) or an increase (Prop. 3) of the adiabatic gas phase flame temperature. The last three propellants, Props. 4 through 6, represent constant O/F ratio propellants with the percentage of

aluminum reduced from 15 percent for the baseline to 10, 5, and 0 percent, respectively. That is, the gas phase flame properties are expected to remain constant while the percentage of aluminum present within the propellant formulation is systematically reduced. A comparison of the burning rate characteristics of Props. 1, 4, 5, and 6, should add insight as to the effect of varying aluminum mass fraction for propellants for which the O/F ratio is held constant. Additionally, the propellant ingredient mass fractions for Prop. 4 and 5 have also been selected to have the expected aluminum agglomerate size decrease as the percentage of aluminum decreases. Once again, this statement has the simple "pocket model" as its basis [8].

For comparison purposes, Prop. 2 has also been selected to be nearly identical to one of a series of unimodal, AP-based propellant formulations investigated by Grigoryev, et al. [9]. In this reference, aluminum agglomeration data is reported at pressures of 1, 20 and 40 atmospheres.

The servo-positioning strand window bomb described in the previous section was currently being employed to obtain burning rate data for these six propellant formulations at atmospheric pressure. Experiments have indicated that the baseline propellant, Prop. 1, burns at approximately .80 mm/sec. Decreasing the O/F ratio (Prop. 2) considerably reduces the burning rate to half that value (atmospheric combustion for this propellant is very erratic, with extinguishment of burning experienced if N₂ purge gas is used). As expected, increasing the O/F ratio (Prop. 3) causes an increase in the burning rate to approximately .96 mm/sec. There was a slight increase in the burning rate observed as the aluminum mass fraction was systematically decreased (Prop. 4 and Prop. 5) with the non-aluminized formulation (Prop. 6) having a burning rate of .88 mm/sec.

IV. IMAGING-TYPE PARTICLE SIZE ANALYZER

The imaging-type, particle size analyzer currently being employed was originally designed by Southern Research Institute for the Parker-Hannifin Corporation to measure liquid fuel spray concentrations. With this machine, a fuel spray could be sample 15 times a second with the data obtained with each sample being processed prior to the next sample being taken. The measured concentrations (in droplets per cubic millimeter) were then displayed in 6 binary size ranges from 8 microns to 512 microns after a pre-determined number of samples were taken. The overall imaging system was functionally divided into five major subsystems. These being: (1) droplet detection, (2) video processing, (3) conversion, (4) display, and (5) readout.

Over the past few years, this device has been modified [3,4]. Although the first two subsystems remain almost identical both mechanically and electronically, the functions of the latter three subsystems are now performed by a PDP-11 mini-computer. The mini-computer also controls the positioning and sampling of the droplet detection equipment while storing the processed data after each sample is taken. With this added flexibility, the spray analyzer has thus been modified to have the capability of determining the local variations in droplet size distribution within the fuel spray under investigation.

The first major subsystem of the spray analyzer deals with droplet/particle (depending on the application) detection. This subsystem consists of an illuminator, a closed circuit television camera, and a video monitor. The sampling of the test volume is accomplished by means of a high intensity, short duration light source - or illuminator. This light source is a xenon flash lamp powered by a parallel capacitor and is triggered by an exter-

nal electrode. Since the test volume is positioned between the illuminator and the television camera, droplet/particle images appear dark on a light background projected on the face of the camera vidicon. The operation of the illuminator is synchronized with the camera so that the flash occurs during the vertical retrace of the camera. Images of the droplets/particles detected during the flash are stored on the photo-sensitive surface of the vidicon. The vidicon surface is then scanned and the droplet/particle images are converted into an electronic signal. This electronic signal is then sent to the second subsystem, the video processing unit, described below. The television camera used is a high performance closed circuit television camera manufactured by Motorola. This camera is equipped with a hetero-junction vidicon which is extremely sensitive to low light levels, especially in the near infra-red. The video monitor is a high resolution monitor, also manufactured by Motorola, and is provided to aid the operator in setting up (calibration and alignment) and using the instrument.

The electronic signal from the scanned vidicon surface is sent to the video processing subsystem where it is analyzed to yield the size of each droplet/particle image and the number of images in each sample. The size of the droplet image is determined by the number of horizontal scan lines intercepted on the face of the vidicon. For the instrument in its present configuration, the combination of optics and vidicon surface area results in each horizontal scan line representing approximately 4 microns. The video processing circuits count the number of scan lines an image intersects and sends this count to the mini-computer where the number is converted to droplet/particle size and subsequently stored. The view volume between the camera and the illuminator is very small, ranging from 2 to 10 cubic millimeters. This view

volume is determined by the lens systems of the camera and illuminator and also by the usable area of the vidicon face. As the droplets/particles pass in the vicinity of this view volume, some will be outside this volume and will appear as blurred images on the face of the vidicon. Therefore, a focus detection circuit is employed to sense the images that are out of focus in order to prevent them from being counted. Since this view volume varies with the dimension of the droplet/particle being observed, calibration must be performed prior to operation using known droplet/particle sizes. Such calibration data is then used in the data reduction program in order to compute actual number densities.

When a very dense spray or gas/particle mixture is being observed, images will be obtained during each sample. Under such conditions, more than one image may intercept one or more common horizontal scan lines. In this event, the information from only one of these images would be used, because the video processing circuits can handle only one bit of information in each horizontal scan line. However, this instrument has been built with three parallel video processing channels, which enables it to process up to three images which intersect a common horizontal scan.

As stated previously, the PDP-11 mini-computer performs the function of the original remaining three subsystems; the conversion, display and readout. Having taken a predetermined number of samples, the software developed for this machine takes the data obtained and using the prior calibration data, calculates number densities for the spray or gas/particle mixture being observed. Further software developed for this system enables plots of the droplet/particle number densities obtained to be generated on the Printronix printer tied to the mini-computer. Sample number density plots for fuel-type

sprays can be observed in Refs. 3 and 4.

Figure 1 is a schematic of the experimental setup of the servo-positioning strand window bomb and the imaging-type, particle size analyzer. With the combustion bomb located in the center, two perpendicular optical axes are arranged such that the investigated view volume above the propellant surface is located at the point of their intersection. The first axis is used by the tracking laser/photo detector arrangement employed by the servo-positioning feedback circuitry. The second optical axis is used by the particle analyzer. The pulsed flash source, or illuminator, is located on one side of the bomb while the video camera-based particle analyzer is situated on the other side. The electrical signal from the video camera is fed to the electronic package which performs the particle detection/video signal processing. As indicated on this figure, both the servo-positioning feedback circuitry and the particle size analyzer are controlled by a PDP-11 mini-computer. From the positioning information, burning rate and instantaneous surface position data is collected and analyzed. Likewise, the mini-computer also processes and stores information concerning the particle size distribution observed during a test sequence. Finally, a Printronix printer is online to give hard copy output of these results.

The following two figures, Figs. 2 and 3, are provided to aid in the brief description of the operation of the electronics involved in the particle analyzer that follows. Figure 2 is a block diagram representing functionally the various components of the electronics. To the far left of the figure is the camera/illuminator combination with the test volume located in between. The composite video signal is fed to the first of a series of electronic components. First, the horizontal and vertical synchronization pulses are

stripped off the video signal. The vertical sync pulses are used to synchronize the flash lamp within the illuminator subassembly. Therefore, the illuminator is designed to flash during the vertical retrace of the video camera.

The video signal is then amplified and the horizontal blanking level is set. If a particle is detected, that is, if the level of the video signal indicates the presence of a darkened area on the vidicon caused by the shadow of a particle within the view volume, a video detect pulse is generated. This video detect pulse is subsequently sent to the input gates of each of the three parallel channels. The first particle detected on a frame is sent to channel one of the analyzer. A look pulse is generated which is basically the video detect pulse delayed approximately the time required for the sweep of a single horizontal raster line ($1/15,750$ sec). Whenever this signal is generated the input gates on the other two channels are turned off and the analyzer tests for the presence of an additional video detect pulse. If these two pulse signals coincide, then the binary counter for that channel is incremented signifying that the particle is still being detected on the vidicon face. Eventually, the occurrence of a look pulse without a corresponding video detect pulse indicates that the particle is no longer being scanned. Upon satisfying this condition, a count pulse is generated instructing the output latches on the binary counter to hold the resultant raster line count for that particle. The PDP-11 then is instructed to interrogate the output latches to acquire the particle size count, reset the binary counters, and wait for another count pulse from that or another channel.

Since the look pulse generator for a particular channel sends its signal concurrently to each of the other two channels, these channels are electronically switched off to the possibility of sensing a video detect pulse during

that time interval. In this manner, three particles can alternately intersect the same horizontal raster line, with the binary counters being incremented for each particle in turn. Figure 3 is a representation of a possible vidicon image containing a number of particles some of which intersecting the same horizontal raster lines. Since the large particle in the upper left corner of this display is the first to intersect a raster line, it would be processed by the first channel (therefore labeled with a 1). On the same raster line over to the right, a second particle has been assumed to be present. Therefore, the video detect pulse generated would be sent to the second channel (labeled 2) for processing since the other channels would be turned off. Meanwhile, a look pulse corresponding to the first video detect pulse activates the first channel at approximately the time another video detect pulse could be detected if the particle is still imaged on the vidicon face at that location within the video raster scan. Eventually during the scanning process of this example video frame, a third particle is detected between the first two - information for which would be sent to the third remaining parallel channel (labeled 3).

The look pulses and all subsequent count pulses are mixed into the video signal which is sent to a monitor used primarily in the calibration of the particle analyzer prior to operation. In this fashion, an individual particle being imaged appears to be surrounded by a leading edge (indicating the presence of look pulses) and a trailing edge (signifying the concurrence of both a look pulse and a video detect pulse). In this figure, the presence of these pulses have been indicated only for the first of the five droplets shown. Finally, when a video detect pulse is not generated, a broad line signifying the generation of a count pulse is mixed into the video signal informing the

operator that a raster line count, or particle size information, has been sent to the mini-computer.

V. PULSE-LIT PHOTOGRAPHIC TECHNIQUE

With a servo-positioning strand window bomb such as that described above, the surface/near surface environment of a burning propellant strand can be investigated photographically in a fashion better than that achieved to date. One of the major drawbacks associated with conventional, non-positioning strand combustion photography has been that the surface quickly burns out of the depth-of-field (DOF) of the optical/camera system employed. This is especially true for high resolution, micro-photographic studies wherein typically the DOF may be on the order of .1 mm, or 100 microns. Under such conditions, the total observation period may be less than .01 second (assuming a typical 1 cm/sec propellant burning rate).

There are two areas of concern associated with the use of conventional photographic techniques in the study of propellant combustion. The first concern deals with the degree of magnification and/or the resolution of the film employed (this is typically defined in terms of the number of line pairs per millimeter). In other words, the limit of the spatial scale that can be resolved with such photographs is important to the study of surface/near surface combustion detail. In regard to aluminum combustion photography, the second concern arises from the appearance of a bright "aureole" surrounding the burning aluminum particle/agglomerate - thus preventing acquisition of true particle/agglomerate size distribution information.

We investigated the feasibility of using a pulse illumination photographic technique similar to that employed by Grigoryev, et al. [9] to study

aluminized propellant combustion, especially within the surface/near surface environment. By using such a system, we reduced the problems listed above. Additionally, high magnification photography has traditionally been used to study propellant combustion and to detail surface detail. However, increased magnification results in corresponding loss of depth of field as well as substantial increases in required illumination. Therefore, in order to maintain a relatively high DOF so that surface structure as well as particle interaction/agglomeration detail can be discerned, magnification should be kept relatively low. The use of short pulse width/high power pulsed illumination "frames" the images on the photographic film. The short pulse width will virtually freeze any particle and/or surface motion while avoiding any propellant sample heating that is a distinct possibility in continuous front lit or back lit photography. By taking the lead from the system described in Ref. 9 and filtering out combustion generated self-illumination while using the proper pulse wavelength/film sensitivity combination, both back lit "shadow" photography - thus eliminating the aluminum particle combustion "aureole" effect - and front lit photography should be possible. Reference 9 reported an experimentally determined resolution of at least 15 microns which our calculations seem to verify as being the current lower limit of resolving power typically available with today's camera/lens systems. However, recent photographs taken by Cross [10] utilizing high resolution holographic film (resolution on the order of 103 line pairs per millimeter) provide encouragement to the fact that this lower limit may be reduced. Photographs of the surface/near surface environment of the aluminized propellant formulations have been obtained burning at atmospheric pressure. The purpose of these photographs is three-fold. First, these photographs permit experimental validation of the operation of the servo-positioning mechanism - that is, does the surface

position remain fixed in space during the entire combustion period? Second, the pulse-lit photography permits observation of the size and number of the agglomerates leaving the propellant surface. Finally, the apparent disappearance of the characteristic "aureole" surrounding the burning aluminum particles/agglomerates due to filter/pulse flash combination can be validated.

The last four figures, Figs. 4 through 7, represent a sampling of the photographs taken. In Figs. 4, 6, and 7, burning aluminum agglomerates are visible in the near surface gas phase. In each of these three photographs, the flash lamp back-lit photographic technique has imaged the particle within its surrounding "aureole". Therefore, the true aluminum agglomerate diameter can be observed. Also, in Fig. 5, a surface agglomerate on the order of 400 microns in diameter can be seen. These four photographs are of the baseline propellant formulation, Prop. 1, burning under atmospheric conditions.

VI. CONCLUSIONS

The experimental equipment and techniques used in an investigation of the mechanisms governing formation and subsequent ignition/combustion of metal/agglomerate particles within a solid rocket motor have been discussed. A servo-positioning, strand window bomb has been developed which is capable of holding the surface of a burning propellant strand fixed in space. With this constraint satisfied, the surface/near surface behavior of aluminum particles/agglomerates can be successfully investigated for extended lengths of time. The theory and operation of an imaging-type particle analyzer developed over the past few years has been detailed. Likewise, a pulsed-lit photographic technique has been discussed and several photographs of burning aluminum agglomerates have been presented for validation of employing this

technique within an investigation of aluminum particle/agglomerate surface/near surface behavior. Additionally, a series of aluminized propellants have been selected and atmospheric burning rate data have been collected for each.

VII. ACKNOWLEDGMENTS

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X. STUDENTS COMPLETING THESIS WORK

- [1] Mary Elizabeth Barger - Master's Program, School of Aeronautics and Astronautics, May, 1980. Thesis Topic: "The Effect of Erosive Burning on Temperature Sensitivity in Composite Solid Propellants." Currently employed at the Air Force Rocket Propulsion Laboratory, Edwards, California.
- [2] Jay S. Lilley - Master's Program, School of Aeronautics and Astronautics, Purdue University, December 1981. Thesis Topic: "The Design and Operation of a Servo-Controlled Solid Propellant Strand Window Bomb." Currently employed at the Army Missile Command, Redstone Arsenal, Huntsville, Alabama.
- [3] Kevin N. Nack - Master's Program, School of Aeronautics and Astronautics, Purdue University, December 1981. Thesis Topic: "A Study of the Aerodynamic Breakup of Molten Aluminum Particles in Two-Phase Flow." Currently employed at the Air Force Rocket Propulsion Laboratory, Edwards, California.
- [4] John P. Renie - Ph.D. Program, School of Aeronautics and Astronautics, Purdue University, December 1982. Thesis Topic: "Combustion Modeling of Composite Solid Propellants." Currently employed as a post-doctoral research assistant by the School of Aeronautics and Astronautics, Purdue University.

TABLE 1. PROPELLANT FORMULATIONS

Propellant Number	% Al [*]	% AP ^{**}	% HTPB	O/F	Comments
1	15.0	65.0	20.0	3.25	Baseline
2	22.0	48.0	30.0	1.60	Reduced O/F
3	8.5	73.5	18.0	4.10	Increased O/F
4	10.0	69.0	21.0	3.25	Reduced % Al Constant O/F
5	5.0	72.5	22.5	3.25	Reduced % Al Constant O/F
6	0.0	76.5	23.5	3.25	Zero % Al

*Al ~ $18 \pm 4 \mu\text{m}$

**AP ~ $190 \mu\text{m}$ ($\sigma \sim 1.6$)

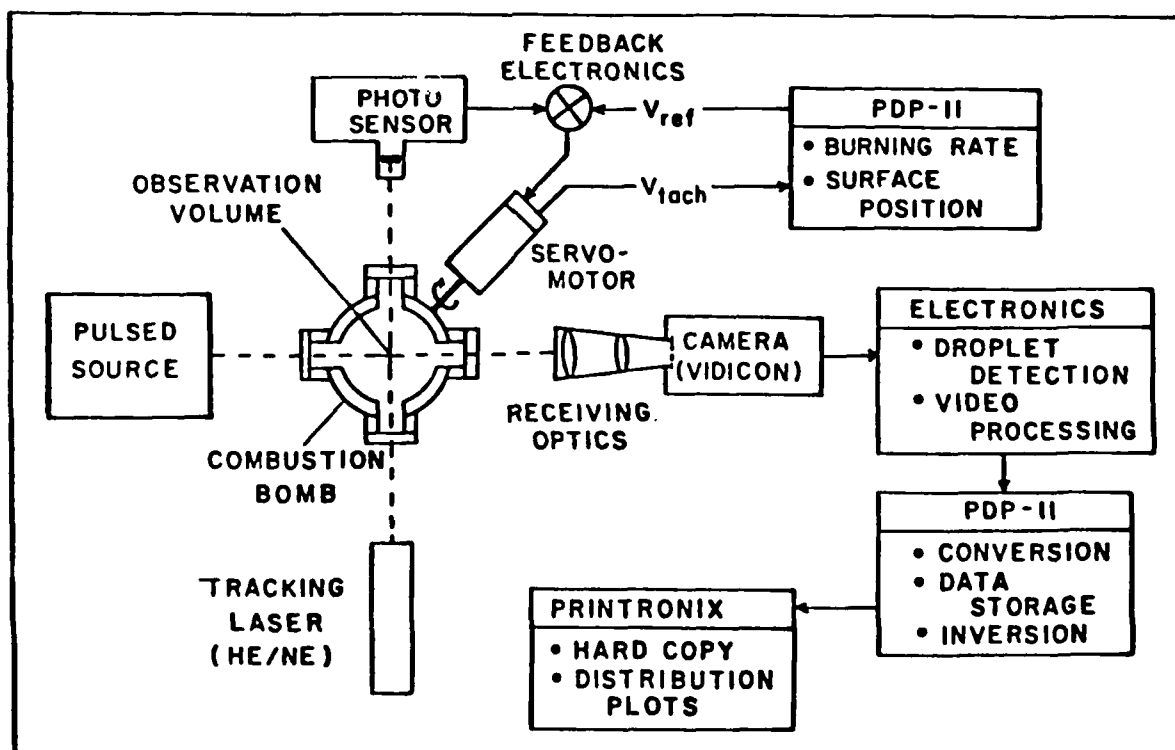


FIGURE 1. DIAGRAM OF EXPERIMENTAL APPARATUS.

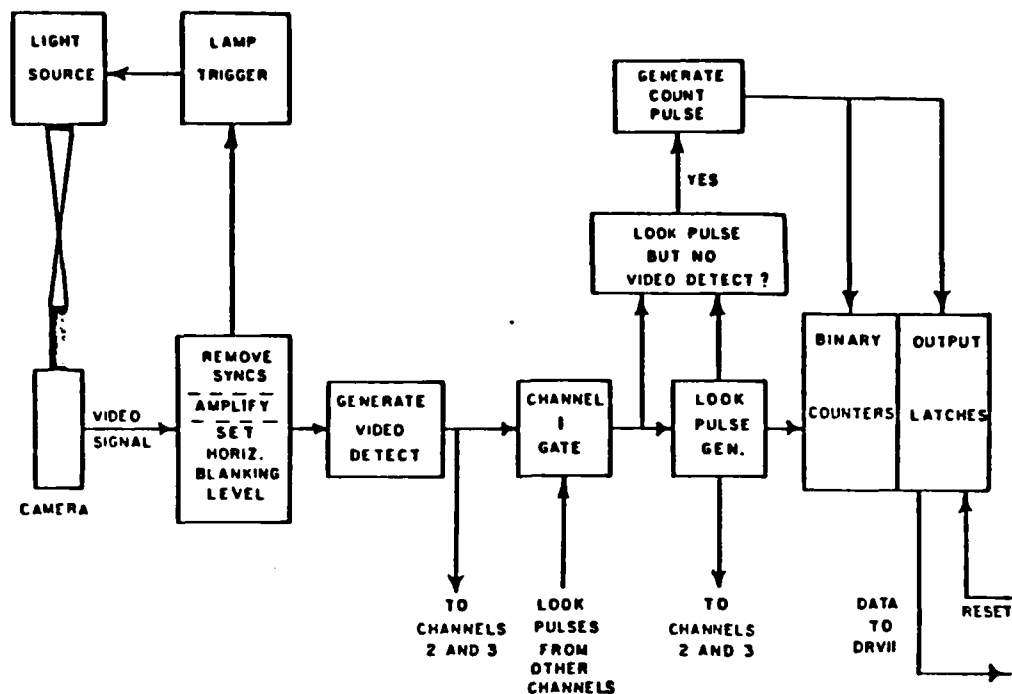


FIGURE 2. BLOCK DIAGRAM OF PARTICLE ANALYZER.

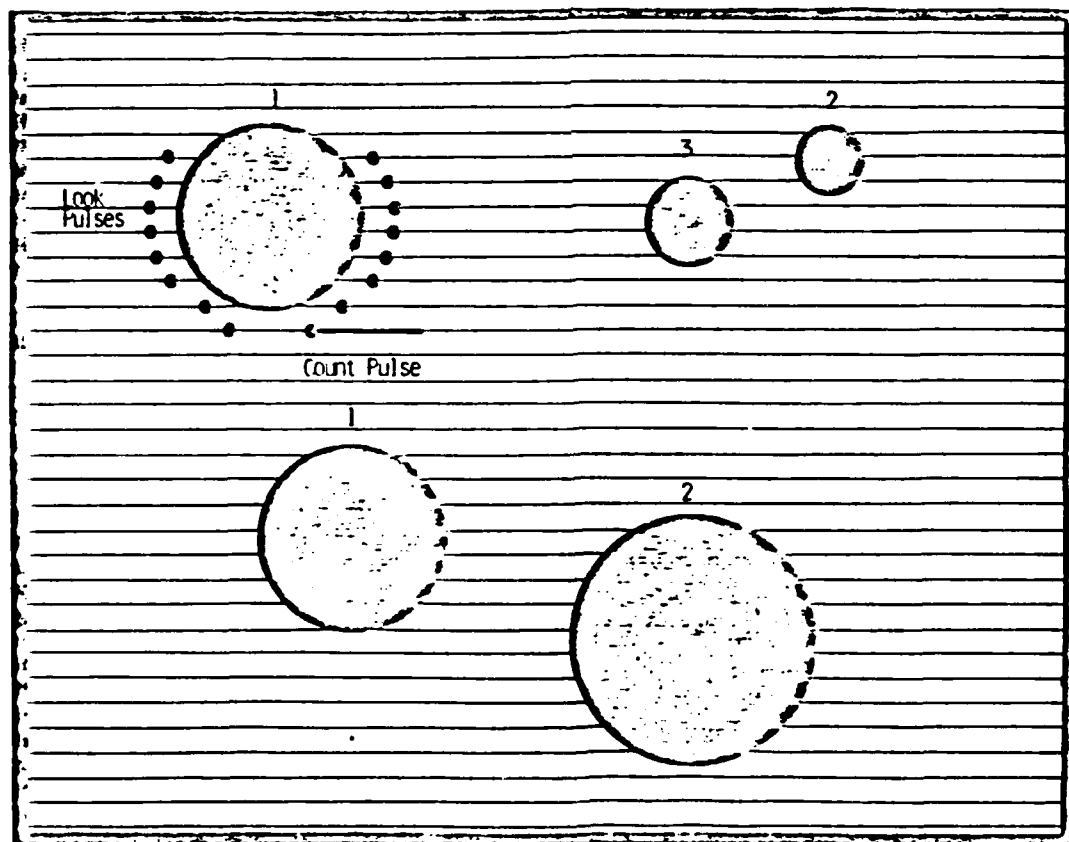
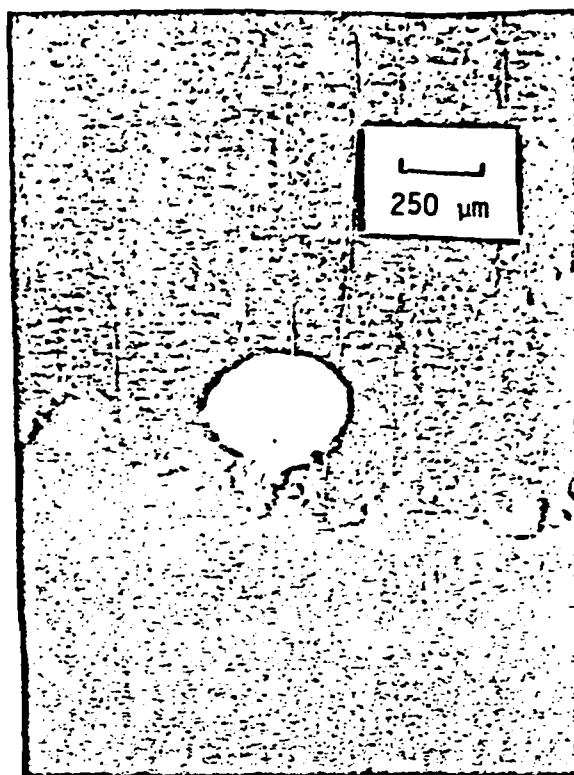
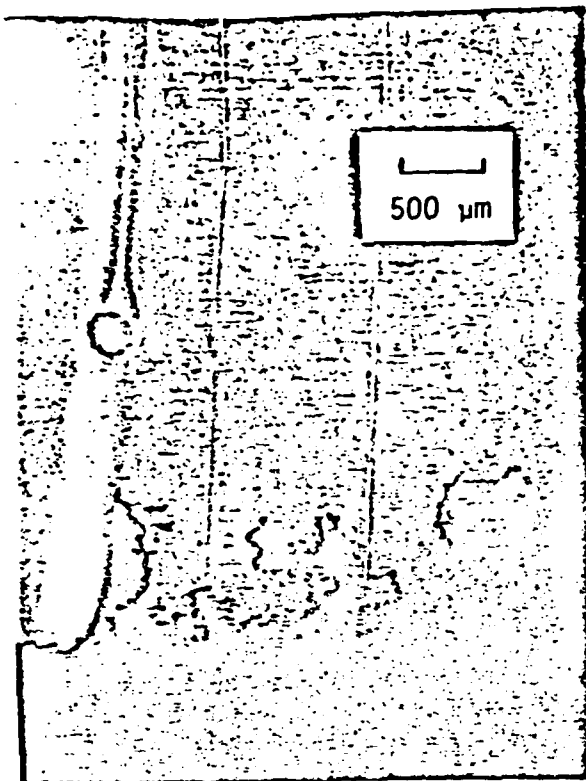
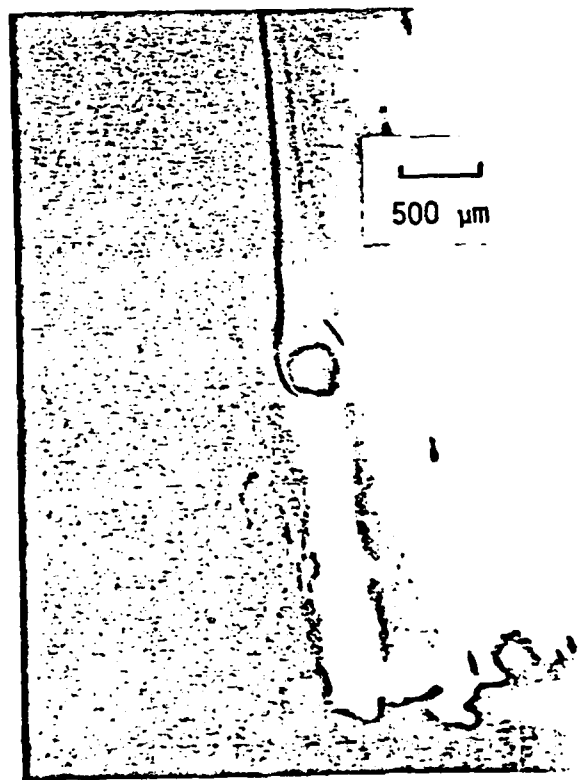
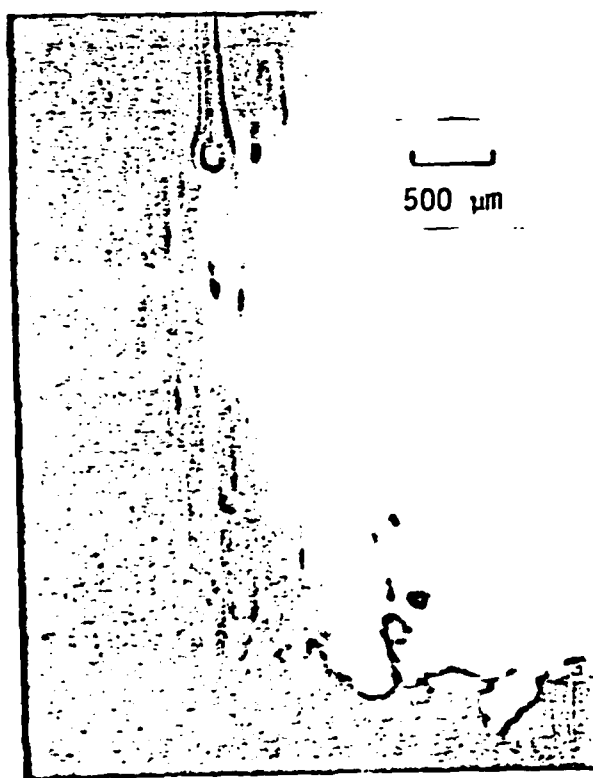


FIGURE 3. REPRESENTATION OF VIDEO RASTER.



FIGS. 4 AND 5. PROP. 1 SURFACE/NEAR SURFACE (1 ATM)



FIGS. 6 AND 7. PROP. 1 SURFACE/NEAR SURFACE (1 ATM)

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